Biodiesel Production and Consumption: Life Cycle Assessment (LCA) Approach

Rajaeifar, Mohammad Ali; Tabatabaei, Meisam; Aghbashlo, Mortaza; Hemayati, Saeed Sadeghzadeh; Heijungs, Reinout

published in
Biodiesel
2019

DOI (link to publisher)
10.1007/978-3-030-00985-4_8

document version
Publisher's PDF, also known as Version of record

document license
Article 25fa Dutch Copyright Act

Chapter 8
Biodiesel Production and Consumption: Life Cycle Assessment (LCA) Approach

Mohammad Ali Rajaeifar, Meisam Tabatabaei, Mortaza Aghbashlo, Saeed Sadeghzadeh Hemayati and Reinout Heijungs

Abstract Like all energy carriers including renewable energies, the production to combustion cycle of biodiesel should also be assessed from the sustainability point of view. Life cycle assessment (LCA) is a promising approach capable of assisting decision makers to find the environmental consequences of the existing or future biodiesel production plans. For instance, for different feedstocks, production technologies, downstream processes implemented, etc., an LCA of biodiesel production cycles could result in different recommendations ranging from agricultural practices to production and combustion stages. Despite the fact that an ISO standard is available for conducting LCA studies, there are still many challenging issues faced when performing LCA studies concerning biodiesel production and consumption. These challenges include the functional unit, the choice of system boundaries, the impact categories to be assessed, the treatment of land use change,

M. A. Rajaeifar (✉) · M. Tabatabaei (✉)
Biofuel Research Team (BRTeam), Karaj, Iran
e-mail: mohamad_rajaei@ut.ac.ir

M. Tabatabaei
e-mail: meisam_tab@yahoo.com; meisam_tabatabaei@abrii.ac.ir

M. Tabatabaei
Microbial Biotechnology Department, Agricultural Biotechnology Research Institute of Iran (ABRII), Agricultural Research, Education and Extension Organization (AREEO), Karaj, Iran

M. Aghbashlo
Faculty of Agricultural Engineering and Technology, Department of Agricultural Machinery Engineering, University College of Agriculture and Natural Resources, University of Tehran, P.O. Box 4111, Tehran, Iran

S. S. Hemayati
Sugar Beet Seed Institute, Agricultural Research Education and Extension Organization (AREEO), P.O. Box 31585-4114, Karaj, Iran

R. Heijungs
Department of Econometrics and Operations Research, Vrije Universiteit Amsterdam, Amsterdam, The Netherlands

R. Heijungs
Institute of Environmental Sciences, Leiden University, Leiden, The Netherlands

M. Tabatabaei and M. Aghbashlo (eds.), *Biodiesel*,
Biofuel and Biorefinery Technologies 8,
https://doi.org/10.1007/978-3-030-00985-4_8

and biogenic carbon. The present chapter provides a systematic overview of the above-mentioned topics with the aim of shedding light on various aspects of LCA of biodiesel production and consumption cycle.

8.1 Introduction

The modern world is heavily dependent on fossil fuels for satisfying its primary needs, particularly, in the industrial and transportation sectors (Rajaeifar et al. 2017a, b). In fact, more than 80% of the current world's energy consumption is fossil-based and projections indicate a continuation of this trend till at least the year 2040 (Ashokkumar et al. 2017). Although concerns with respect to fossil fuel depletion have been considered over time, the major challenge regarding the huge consumption rate of fossil fuels is the environmental consequences caused by their combustion. More specifically, air pollution and the subsequent risks for human health and the environment on one hand and anthropogenic GHG emissions and their subsequent global warming impacts on the other hand are among the most grave challenges faced on a worldwide scale (Hosenuzzaman et al. 2015; Nicoletti et al. 2015; Aghbashlo et al. 2017).

Alternative energy carriers such as biofuels have been widely considered as replacement for fossil sources in order to address the above-mentioned challenges. Biofuels offer numerous advantages including non-toxicity, biodegradability, better emission profiles, renewability, domestic production in many countries, capability to be used as transportation fuels, stimulating the agricultural sector and improving its economic balance, creation of new job opportunities, and providing energy security (Demirbas 2009; Wiloso and Heijungs 2013; Rajaeifar et al. 2016). Nevertheless, there are controversial sides to biofuel production and consumption as well which have been the subject of debates among the global scientific community. These controversies include (1) competition with agricultural food/feed/fiber products and their impacts on the food/feed/fiber price and (2) direct and indirect land use change impacts (Wiloso and Heijungs 2013) which could significantly affect their GHG reduction benefits (Malça and Freire 2011). Moreover, the relatively high cost of biofuels production has necessitated government supports for their promotion (e.g., through subsidies, price guaranteed, lower taxes or tax exemptions) (Rajaeifar et al. 2013).

Among different commercial biofuels, biodiesel is a promising alternative for petroleum diesel and has recently attracted a huge deal of attention in the transportation fleets around the world (Demirbas 2009; Jiaqiang et al. 2016). Biodiesel, also known as mono-alkyl esters of different long chain fatty acids, is derived from a variety of renewable lipid sources (Ghobadian et al. 2009). Possible feedstocks used for biodiesel production are generally classified into three different groups, i.e., (1) first-generation feedstock (mainly edible oils), (2) second-generation feedstock (mainly nonedible or waste oils), and (3) third-generation feedstock (mainly related to algal biomass but to a certain extent linked to utilization of CO_2 as feedstock

(Lee and Lavoie 2013)). First-generation biodiesels are readily available and widely used due to the fact that they can be produced from a wide range of feedstocks and through well-developed production technologies. Nevertheless, their production and development has triggered a debate on controversial competition with agricultural food/feed/fiber products while it has also led to direct and indirect land use change impacts.

The second-generation biodiesel fuels have been able to rectify the problems associated with their first-generation counterparts, but they may also create an indirect competition between the biodiesel industry and the industries in which waste feedstocks are currently used. Moreover, nonedible and waste-oriented oil feedstocks generally require several extra energy-intensive processes during feedstock preparation, which could also potentially increases indirect land use change impacts (Singh et al. 2011). The third-generation biodiesels are assumed to be free of such problems. However, several studies have shown that industrial-scale algal cultivation also requires a considerable deal of nitrogen and phosphorous supplementation used in form of fertilizers. This may seriously endanger the potential advantages of the third-generation feedstocks since the upstream activities of fertilizer production impose heavy burdens on the environment. For example, in comparison to rapeseed biodiesel, biodiesel from microalgae needs 55–111 times more nitrogen fertilizer—i.e., 8–16 tons/ha/year (Demirbas 2011). Such considerations suggest that even when biodiesel would be environmentally superior during combustion; it may have downsides during production. As such, a life cycle perspective is needed. In addition to that, given the free-fall of the prices of petroleum products in response to the recent developments, e.g., emerging of the shale oil extraction technology, the economic viability of algal biodiesel for short-term and medium-term applications is also questionable.

Among the advantages of biodiesel is its environmentally friendly emission profile compared with petroleum diesel, i.e., decreased emissions of CO, unburned hydrocarbons (UHC), and particulate matter (PM), as well as decreased smoke opacity (Kumara et al. 2009; Lee et al. 2011). Moreover, biodiesel contains no sulfur and aromatic compounds in its chemical structure leading to a cleaner combustion compared with its diesel counterpart. Nevertheless, it has been reported that biodiesel generally increases tailpipe emissions of CO_2 and NO_x (Sheehan et al. 1998; Mohammadi et al. 2012).

In spite of all the mentioned benefits associated with biofuels utilization as an alternative for fossil fuels, sustainability assessments criteria should still be taken into account during decision-making and policy-making processes. Based on the definition presented by the World Commission on Environment and Development, the term "sustainable development" is defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs"(UNCED 1992). Accordingly, three important dimensions of sustainability, namely social, environmental and economic form the backbone of sustainability standards which must be considered in sustainability assessment of any products or services as much as possible (Elkington 1997). Similarly, the general principles of sustainable biofuel production and consumption could be easily defined but establishing a sound framework in order to efficiently characterize these impacts is quite challenging due to the complicated interactions among these three different dimensions (Singh et al. 2013).

Currently, environmental assessments—consisting of their very own frameworks—are generally accompanied by the other types of sustainability assessments, e.g., social and economic assessments, or they are solely used for environmental sustainability assessment purposes. Life cycle assessment (LCA) is one of the assessment methods widely used for inspecting the environmental impacts of a product/system (Guinée and Heijungs 2017) and is also the most widely used technique for assessing the environmental balance in biofuel production and consumption chains.

LCA is generally defined as a tool or approach that helps to assess the environmental impacts of a product/service throughout its life cycle (Guinée 2002; Lin et al. 2013). More specifically, it is capable of attributing the possible consequent threats to the human health, natural ecosystems, and resources through different damage assessment mechanisms. From the methodological point of view, LCA deals with such questions by using a system approach, i.e., considering the product (in this case biodiesel) as "a product system" or in better words, as "a function system". In fact, this approach considers the entire life cycle of a product/service, from extraction of natural resources to the final waste management of the disposed product, or so-called from "cradle to grave" (Guinée and Heijungs 2017). Of course, a legitimate question may arise about the necessity of employing LCA in some cases where the best scenario could be easily found by intuition. The answer is that even when dealing with the simplest problems, the reality could be much more complex and a systems approach is required to map the whole life cycle and all potentially relevant environmental impacts (Guinée and Heijungs 2017). For instance, it may be advocated that using electric vehicles is simply way better than driving gasoline-driven vehicles from the environmental perspective because they are "zero emission" vehicles. However, an LCA study showed that the results could be heavily dependent on the source of electricity and/or consumer's behavior (Hawkins et al. 2013).

ISO standards–14040-46—proposed a standardized method for conducting LCA studies, in which many criteria have been defined and guidelines have been proposed ranging from basic issues, i.e., goal and scope definition, inventory analysis, life cycle impact assessment, and interpretation to emerging crucial and complicated problems, i.e., eco-efficiency assessment (ISO14045 2012) and water footprint (ISO14046 2014). In fact, the ISO series 14040 has been the most successful attempt in harmonizing LCA studies to date. Nevertheless, there are still many challenging issues faced when performing LCA studies in practice concerning bioenergy feedstocks. This is due to the fact that such systems directly or indirectly involve an agricultural stage which brings some complex and challenging issues in estimating the real environmental impacts. Moreover, indirect inclusion of agricultural stage implies more agricultural cultivation in other parts of the world, and thus increases the uncertainty in the environmental impacts calculations. There are also many other complicated factors coupled with an increased agricultural cultivation including economic, market, land occupation, and agricultural management issues which may add to the uncertainty level of the cycle. In addition to that defining a functional unit, choosing of system boundaries, selecting impact categories, and the treatment of land use change as well as biogenic carbon are the most prominent technical and practical issues which should be tackled in order to increase quality and usefulness of LCA results.

The present chapter provides a systematic overview of the above-mentioned topics with the aim of shedding light on various aspects of LCA of biodiesel production and consumption cycles. Section 8.2 discusses the general stages in life cycle of different biodiesels including the main area in data collection and scenario design in LCA studies. In Sect. 8.3, some issues and challenges faced in conducting LCA of biodiesel production/consumption systems are comprehensively elaborated. Finally, some recommendations to perform more accurate LCA studies on biodiesel production/consumption systems are included in Sects. 8.2 and 8.3.

8.2 Biodiesel Life Cycle Stages: A Brief Description

Before conducting an LCA study on a given biofuel, it is very important to understand and determine every stage of the life cycle. This could help to perform a comprehensive LCA in form of "well-to-wheel" in case of biofuels. More specifically, this would avoid overlooking a stage/substage in the life cycle and could also help with detailed inventory data collection at the time of performing the project or collecting data from databases. Neglecting a stage/substage in the life cycle causes increased uncertainty, increased time and costs related to recalculating the neglected stage/substage in the life cycle while also making the comparison of the results incorrect or impossible. Overlooking one or some of the stages/substages involved in the life cycle is an error observed in some studies on LCA of biodiesel (Rajaeifar et al. 2017b). For example, there are studies in which the scope of the study did not clearly define the inclusion of the combustion stage, while other studies failed to define transportation of diesel and biodiesel from the production source to the point of use, transportation of goods (input materials) to the agricultural farms, etc. Therefore, all stages involved in the life cycle of a given biodiesel must be determined before conducting an LCA study and those stages must be clearly mentioned through the scope of the study and illustrated in the proposed system boundary.

Stages involved in the life cycle of biodiesel may be defined based on the feedstock used for biodiesel production, i.e., from the first- to third-generations. Figures 8.1, 8.2, and 8.3 briefly show the possible stages involved in the life cycle of these three biodiesel generations. It should be mentioned that different technologies may include more or fewer substages, but the general scheme of the stages involved in different biodiesel generations is similar to the ones presented in these figures. Based on Fig. 8.1, LCA of biodiesel production/consumption using first-generation feedstock generally encompasses the following main stages:

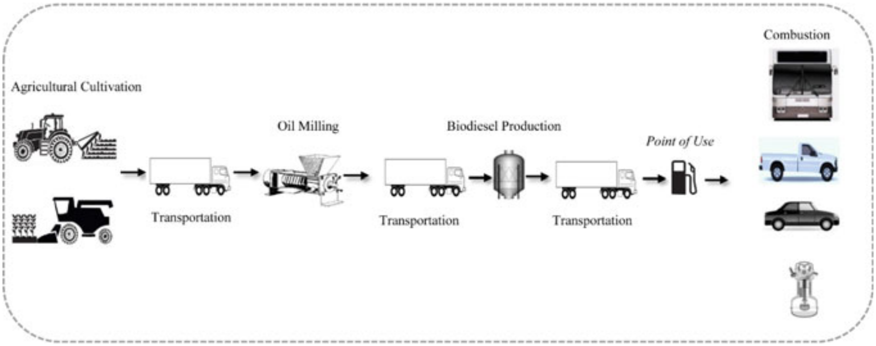

Fig. 8.1 Simplified flow diagram of the well-to-wheel processes involved in the first-generation biodiesels' life cycle

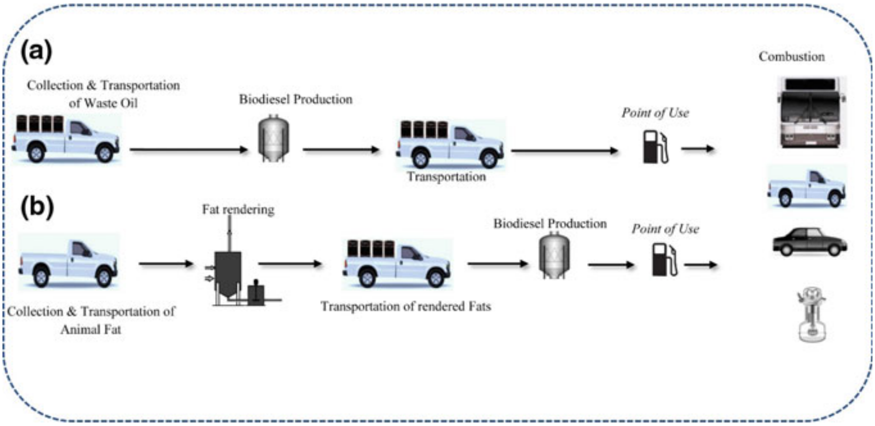

Fig. 8.2 Simplified flow diagram of the well-to-wheel processes involved in the second-generation biodiesel life cycle (**a** waste oils and **b** animal fat)

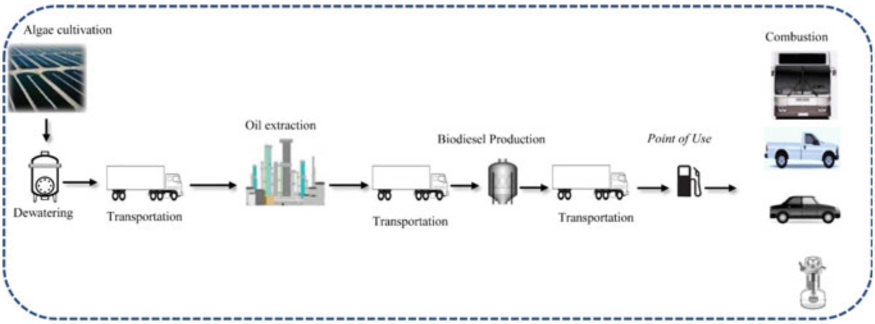

Fig. 8.3 Simplified flow diagram of the well-to-wheel processes involved in the third-generation biodiesel life cycle

agricultural cultivation, transportation, oil milling (oil extraction), as well as biodiesel production and combustion. The ***agricultural cultivation stage*** could further be divided into the following substages: upstream activities for the production of agricultural inputs (e.g., seed, fertilizers, pesticides, fuels, etc.), production of capital goods (e.g., agricultural buildings and machinery), and fieldwork operations (e.g., land preparation, planting of seed/seedlings, fertilizing, tillage, harvesting, etc.). It should be mentioned that there is a difference between annual and perennial crops in the agricultural cultivation substages. In other words, perennial crops generally need pre-nursery, nursery, and immature plantation (or two of these) substages before annual plantation activities. These substages may take place during several years and must be included in the assessment. In this regard, the consumption of agricultural inputs, emissions originated from upstream activities for the production of these inputs as well as emissions originated from the above-mentioned pre-cultivation substages should also be considered. More specifically, all the agricultural activities (from pre-nursery activities to the agricultural actives in each cultivation season) should be taken into account throughout the lifetime of a crop (e.g., 25–28 years for palm oil trees and 25–30 years for olive trees) and the inventory for a cultivation year should be obtained as the average of these years. This approach has been well employed by many researchers (Schmidt 2007; Choo et al. 2011; Van Zutphen and Wijbrans 2012; Rajaeifar et al. 2016) while there are also a number of studies in which these substages were left out.

Since the second-generation biodiesel feedstocks are generally considered to be waste, useless or low price fat/oils, analyses do not include the agricultural cultivation stage, and thus no environmental burdens are carried from their first life (Fig. 8.2a, b). It should be noted that in the case of nonedible oil feedstock specifically cultivated for biodiesel production, their agricultural cultivation stage should also be included. As for animal fats (Fig. 8.2b), the upstream activities related to animal husbandry and slaughterhouse are generally excluded since fat is usually traded at far lower prices in comparison with meat (i.e., an increase in demands for animal fats would not serve as a motivation for meat producers to increase their meat production) and moreover, a proportion of animal fats is generally subjected to disposal in many parts of the world. This approach has been used by many reports published previously (Dufour and Iribarren 2012; Jørgensen et al. 2012; Escobar et al. 2014; Rajaeifar et al. 2017b). For the third-generation biodiesels (Fig. 8.3), the agricultural cultivation stage includes the cultivation of algae in pounds. In such systems, a pre-cultivation stage, i.e., the cultivation of an algal strain in photo-bioreactors/indoor ponds to be used as inoculum (seed culture) for the open ponds, should also be considered (Sander and Murthy 2010). It should also be noted that ***dewatering*** is a different ***stage***, which must be inventoried separately.

In the ***transportation stage***, all the relevant transportation activities are included and the inventory data generally include the consumption of materials by vehicles (from fuels to engine oils and filters), production of capital goods, and construction of the infrastructure. However, the calculation of the last two items is difficult and could bring about uncertainties since vehicles or roads used could, in general, have other applications rather than being solely used for biodiesel transportation. Based on Fig. 8.1, transportation of the agricultural outputs to the oil mill plant, transportation of the extracted oil to the biodiesel production plant, and transportation of biodiesel to the point of use are the main substages which are generally included in the assessment. It is also worth quoting that transportation of agricultural inputs to the farms as well as transportation of input materials to the oil mill and biodiesel production plants are generally included in their related stages rather than in the transportation stage (Escobar et al. 2014; Rajaeifar et al. 2014). The transportation substages for the third-generation feedstocks are the same as those of the first-generation ones (Fig. 8.3). However, for the second-generation biodiesels (Fig. 8.2a, b), there is no agricultural output transportation and instead, collection and transportation of feedstock from the point of generation to biodiesel production plants (or in the case of animal fats, the transportation of feedstock to rendering plants and then to biodiesel production plants) are considered. Nevertheless, if a consequential approach is employed, agricultural stage and its relevant substages might also be potentially included for the second-generation biodiesels as well. Overall, a more detailed inventory data for transportation in a life cycle could be helpful in further optimizing the transportation distances based on the final results and the environmental hotspots found in the life cycle.

In the ***oil mill stage***, the agricultural output is converted into oil and meal. There are many oil extraction methods such as cold pressing, pressing and extraction by organic solvents, microwave or ultrasound-assisted methods (Moreno et al. 2003; Shah et al. 2005; Rajaeifar et al. 2013) with their own pros and cons. It should be mentioned that most modern oil extraction technologies are based on lowering the volume of wastewater produced in the oil milling process, while more efficient methods for treating the generated wastewater are also in development (Hodaifa et al. 2013; Lim et al. 2014; Liew et al. 2015; Yu et al. 2017). From the LCA point of view, the oil mill stage could further be divided into the following substages: upstream activities for the production of input materials needed for oil milling (e.g., chemicals, fuels, electricity, etc.), production of capital goods, and oil mill plant operations (e.g., oil extraction, wastewater treatment, meal drying, etc.). This is also applicable to the third-generation feedstocks (Fig. 8.3). As mentioned earlier, transportation of the input materials to the oil mill plant is generally included in this stage as well. For the second-generation feedstocks, there is generally no oil mill stage included unless in the case of animal fats where further rendering is required (Fig. 8.2b).

The oil extracted in oil mill stage is transported for further conversion into biodiesel in the ***biodiesel production stage***. The type of the conversion technology used for a dedicated biofuel may have a significant impact on its life cycle emissions, at a lower magnitude in comparison with feedstock production (i.e., agricultural cultivation) stage though (Wiloso and Heijungs 2013; Altamirano et al. 2016). Among the different methods used for biodiesel production, transesterification has been considered by far as the best method (Baskar and Aiswarya 2016) and is the most prominent technology used at commercial scale as well (Stojković et al. 2014). More specifically, transesterification is the reaction of triglyceride molecules present in fat or oils with an alcohol resulting in the formation of mono-alkyl esters (biodiesel) and glycerol (Ma and Hanna 1999). The conventional transesterification reaction is mainly highlighted by heating and stirring the reaction mixture (to stimulate a quick contact between reagents), consumption of a high amount of energy for heating and stirring, relatively high temperature (i.e., slightly below methanol boiling point of 65 °C), and using homogeneous/heterogeneous acid or base catalysts (Sáez-Bastante et al. 2015; Rajaeifar et al. 2017a). However, different attempts have been made with an aim of introducing new techniques in order to further enhance conventional biodiesel production from different aspects of energy consumption, time, biodiesel conversion efficiency, wastewater generation, and production costs. Some of these techniques include nanocatalytic technology, ultrasound-assisted, microwave-assisted, in situ transesterification, supercritical (catalytic or non-catalytic), subcritical, and membrane-assisted techniques (Georgogianni et al. 2008; Motasemi and Ani 2012; Sáez-Bastante et al. 2015; Rajaeifar et al. 2017a; Tran et al. 2017). The biodiesel production stage can further be divided into substages, such as upstream activities for the production of input materials needed for biodiesel production (e.g., chemicals, electricity, etc.), production of capital goods and biodiesel production plant operations (e.g., biodiesel production, biodiesel refining, wastewater treatment, etc.). This is also applicable to the second- and third-generation feedstocks. Similar to the oil mill stage, transportation of the input materials to the biodiesel production plant is generally included in this stage as well.

The ***combustion stage*** is the final stage in a 'well-to-wheel' life cycle of biodiesel in which tailpipe emissions from stationary or mobile engines running on biodiesel are measured. The required inventory data on tailpipe emissions can be collected through laboratory chassis dynamometer tests (steady-state operation also known as bench-scale examination) or real-world tests. Laboratory chassis dynamometer tests are commonly performed based on standard driving cycles at considerably less costs and experimental burdens while real-world tests need rigorous operational considerations and impose higher costs for monitoring emissions when the vehicle is in motion. The combustion stage only considers tailpipe emissions, and thus has no further substages. It is also worth quoting that in case of using biodiesel–diesel blends or additives in biodiesel, the upstream activities related to diesel or additive production and transportation must also be inventoried separately (Xue et al. 2012; Rajaeifar et al. 2017b). Moreover, there is no difference between the different generation feedstock in preparing the inventory data for this stage.

8.3 LCA and Biodiesel Production/Consumption Systems: Some Issues and Challenges

At the first glance, applying LCA in biodiesel production/consumption systems seems like the other products or services in which LCA could be practically applied. In another word, the choices within the four main phases of LCA (i.e., goal and scope definition, inventory analysis, impact assessment, and interpretation) seem clear and apparently easy to be made, similar to LCAs of other products. However, a more in-depth look would reveal that in practice, conducting an LCA of biodiesel production/consumption systems is more difficult and complicated due to data variability (mainly in the agriculture, biodiesel production, and combustion stages) as well as the additional challenges and uncertainties in the currently used methodological approaches. More specifically, such systems mainly involve an agricultural stage, or they would imply more agricultural cultivation in other parts of the world, thus introducing challenges and complexities in the calculation methods as well as increasing the level of uncertainty in the environmental impacts calculations. The other reason is that biodiesel development is coupled with many other complicated factors originated from changes in demand and supply chains in the market (locally or globally) or agricultural land occupation. Moreover, there are also technical and practical issues in the methodology of LCA; some of which are still the subjects of ongoing discussions among academics (i.e., functional unit, the choice of system boundaries, the impact categories to be assessed, the treatment of land use change, and biogenic carbon). These issues and challenges have also caused a wide range of outcomes even for apparently similar biofuel life cycles. The present section provides a systematic overview of the above-mentioned topics and challenges.

8.3.1 Goal and Scope Definition

The goal and scope definition is a very important initial step in every LCA study. This is due to the fact that goal and scope definition is the starting point of a research work which could directly affect many choices used throughout the course of the study. Choosing attributional or consequential approach alongside choosing the system boundaries, functional unit and dealing with multifunctional processes, as well as the types of required inventory data are among the methodological choices which follow the goal and scope definition (Wiloso and Heijungs 2013). The goal of an LCA study determines the context of the study, its intended application, and targeted audience while the scope definition outlines the type of methodology to be used in the subsequent modeling (Baumann and Tillman 2004; Wolf et al. 2010).

It should also be noted that a well-defined scope and boundaries are essential for guaranteeing a well-defined goal (Curran 2017). Therefore, the following six aspects are recommended to be addressed and documented during the goal definition process (Wolf et al. 2010):

- The intended application(s)
- The reasons for carrying out the study
- Limitations regarding the method, assumptions, and impact categories used
- The intended audience
- Whether the results are to be used in comparative assertions and planned to be disclosed to the public
- The commissioner of the study and other influential actors.

Scope definition embraces a set of major choices which must be clearly explained through the course of each LCA study, i.e., studied system or process and its function, system boundaries, functional unit, modeling approach (consequential or attributional), as well as the reference system or flow to be used. Moreover, scope definition should lead to the determination of the following issues: the type of required inventory data and the data quality requirements, life cycle inventory (LCI) modeling framework, treatment of multifunctional processes and products, impact categories to be covered, selection of life cycle impact assessment (LCIA) method and if included—data normalization and weighting factors, and treatment of uncertainties (Wolf et al. 2010; Heijungs and Wiloso 2014). Moreover, neglecting, removing or merging stages/substages must be clearly explained in the scope definition as it could be misleading when interpreting the results. It is worth quoting that unlike what is suggested by the ISO standard on goal and scope definition, no concrete details on system boundaries, impact categories, and treatment of uncertainty are allowed to be implemented at this stage (Heijungs and Wiloso 2014). In better words, such details should be collected and analyzed in the inventory phase and the impact assessment phase of the study, respectively, and not in the goal and scope definition.

8.3.1.1 System Boundaries

As one of the most important aspects of the goal and scope definition, system boundaries influence data collection, background data choices, and foreground modeling aspects (Baitz 2017). System boundaries must be well designed in a way that correctly present an overall perspective of the life cycle stages involved, main relevant (unit) processes/flows, main input(s)/output(s), excluded activities (stages/substages), as well as included and excluded emissions from different flows (e.g., tailpipe emissions, wastewater emissions, emission to air/water/soil). Based on the ISO definitions, system boundaries simultaneously separate the analyzed system from the rest of the technosphere as well as the ecosphere (Wolf et al. 2010). Other dimensions beside technical aspects need to be specified clearly as well, i.e., geographic (spatial) and time (temporal) boundaries (Curran 2017). It is also worth quoting that excluding any stages/substages/processes/emissions during an LCA is only permitted if they are estimated to have no significant impacts on the overall conclusions of the study. Examples are construction of capital goods in some cases, human labor, some internal transportation of materials within production facilities, manufacture and transport of packaging materials which are not associated with the final product, maintenance and operation of support equipment, identical stage/substage/process/emissions in comparative LCA studies, or in cases where cutoff may be the only solution (i.e., when the system is theoretically infinitely large). The brief description presented in the previous section could help in arranging convenient system boundaries in LCA of different biodiesel feedstocks and prevent arbitrary system boundaries definition. A word of warning should also be added regarding the importance of the inclusion of a reference system when defining and describing the system boundaries of a study. This generally applies when the goal of an LCA study encompasses a comparison between the main system under investigation and the other systems of comparison value.

8.3.1.2 Functional Unit

The product or process being studied through LCA is described and quantified through a functional unit (FU) specified in relation to the nature of a system, geographical, and time boundaries. In other words, the functional unit is a quantified description of the performance of a product system (Weidema et al. 2004). An appropriate functional unit is the one that positively reflects the reality of the problem. This, in fact, could be achieved when the FU is driven by the main questions or goals of the LCA study. Choosing a proper FU is very important in LCA studies since different choices of functional units from the same system may lead to different results when compared to each other (Wiloso and Heijungs 2013). For instance, comparing two types of paint on a per liter basis may yield a different preference compared to comparing the same paints on a per square meter basis. For LCA of biodiesel systems, the most common FU used in the studies are generally classified into the following four groups (Cherubini and Strømman 2011):

Input-oriented FUs: these types of FUs describe the performance of a system based on input biomass (either in mass or energy unit) and are appropriate to show the best uses for a given biomass feedstock. Examples of such FU applications are 1 kg corn produced, 1 kg or barrel of waste cooking oil collected and transported, and, etc.

Output-oriented FUs: calculating and evaluating the performance of a system based on the unit of output delivered is performed through these types of FUs. It is regularly reported that output-oriented FUs are the most common type in LCA of bioenergy and seems the best option for these systems (Cherubini and Strømman 2011) unless the system delivers multi-outputs and need an allocation procedure like what generally happens in biorefineries. Such FUs generally show the performance of a given biodiesel based on the calorific value of biodiesel (MJ, kWh), mass or volume of biodiesel produced (kg or L), or driving distance of a vehicle (in km) fueled by a given biodiesel blend.

Agricultural land use oriented FUs: here the evaluation of a biodiesel system is performed based on the hectare of land area required to produce the biodiesel feedstocks. This type of FU is convenient for the first-generation feedstocks. Although the application of this type of FU was rarely reported in the literature, it could lead to driving helpful results at policy level since the biomass could bring a competition in land occupation with food/feed/fiber products. Moreover, this type of FU directly shows the efficiency of agricultural management in a dedicated occupied agricultural land. Cherubini and Strømman (2011) remarked that relative land use efficiency (i.e. the use of scarce land resources as efficiently as possible) is found using this type of FU. An example of using agricultural land use as an FU could be found in Lim and Lee (2011) study in which 1-year use of one-hectare palm oil plantation was considered as a FU to produce both biodiesel and bioethanol.

Time-oriented FUs: these types of FUs refer to a period of activity performed by a system, e.g., yearly, monthly or based on a season activity.

Input- and time-oriented FUs as well as the ones based on the unit of agricultural land use do not facilitate a proper comparison between biofuels and their fossil counterparts. Probably, for this reason, output-oriented FUs are the most common type used in the LCA of bioenergy systems (Cherubini and Strømman 2011). This also applies to LCA of biodiesels, for which results based on the volume of biodiesel produced (or combusted) (in liters) seems more perceptible for the public as they see and understand what they finally pay for. This is also the case for policy makers as they are generally offered reports in which consumption of fossil fuels as well as projected substitutions by alternative fuels is presented on a volume basis (i.e., in liters). Nevertheless, it has been reported that when the best use of a given biomass feedstock as bioenergy (heat, electricity, biofuel) is the main question of the study, functional units in the form of one MJ or kWh are more appropriate (Wiloso and Heijungs 2013). Based on literature studies, there are two different perceptions of FU as a unit of energy: (1) the calorific value of biodiesel in forms of MJ and (2) MJ or kWh of useful energy. It is worth quoting that only the second perspective lead to find the best use of a given biomass feedstock as bioenergy since they consider the efficiency of different systems, e.g., efficiency of diesel engines in power plants alongside conversion and transmission losses, while the first perspective only help to find the best technologies, treatment methods or feedstock for biodiesel production.

For LCA studies in which the combustion stage is included or comparing biodiesel and petroleum diesel for transportation is the main question, FUs in the form of distance traveled (in km or miles) by vehicles is more appropriate. However, when measuring tailpipe emissions, the working conditions must be completely similar in order to be able to compare systems based on this type of FU. Moreover, all the experimental details regarding the vehicle traveling must also be reported, e.g., the type of vehicle (s) used along with their model and age, vehicle speed, passenger load (number), and route specifications including the length and grade of the road used in the experiments. Overall, in order to enhance understanding of the system under study and avoid misleading conclusions, using several functional units could be more helpful. This important issue is commonly neglected by the methodological standards for bioenergy systems (Cherubini and Strømman 2011).

8.3.1.3 Attributional and Consequential LCA

In developing LCA methodologies, the distinction between attributional LCA (ALCA) and consequential LCA (CLCA) should be taken into consideration. The specification of the type of LCA used should be firstly shown in goal and scope definition step. This could further influence methodological and data choices for the LCI and LCIA as subsequent steps. The goal of an ALCA study is to assess the environmental burdens attributed to a product/service assuming the current situation (of technology, market, economy, and supply chains) or so-called 'a status quo situation'(Wiloso and Heijungs 2013). This approach describes the environmentally relevant physical flows to and from a life cycle and its subsystems (Ekvall and Weidema 2004). A complete set of procedures and recommendation for a clear goal and scope definition when ALCA is applied were introduced by Martin (2017). It should be highlighted that the static nature of ALCA would not permit this type of LCA to be the central core in decision-making processes for policy makers especially in case of biofuels such as biodiesel and bioethanol. This is due to the fact that this approach does not have the capability of showing the possible changes in environmental impacts regarding possible choices, especially indirect land use change (iLUC) impacts originated from biofuel development. However, ALCA is useful in highlighting the environmental hotspots of the current production systems and determining the differences between feedstocks, production processes, and efficiencies with respect to the overall environmental burdens (Wiloso and Heijungs 2013).

CLCA, on the other hand, expands the system boundaries of an attributional approach so as to embrace possible external consequences in response to possible decisions and changes, and consequently estimates their effects on environmental flows (resource use and emissions) of a given product/service (Finnveden et al. 2009). Therefore, CLCA is in principle more effective and attractive for strategic planning when biodiesel and bioethanol development is the main concern. This approach mainly relies on additional economic data like marginal production costs, elasticity of supply and demand (Ibenholt 2002). The CLCA methodology differs from ALCA not only in goal and scope definition, but also in system boundaries, FU, LCI, and treatment of multifunctional processes (Thomassen et al. 2008). More importantly, CLCA encompasses the indirect effects especially ones related to the land use changes and it employs marginal data while ALCA does not include the indirect effects and it uses average data. This specification has a twofold structure, one which shows CLCA as a more comprehensive method with its advantages. The other aspect shows the complexity of modeling the indirect effects and thus increased uncertainty introduced by this method which may cause to remove the advantages came from this approach. More specifically, the results made by CLCA are strongly sensitive to the assumptions employed by the modeling. Therefore, all the assumptions should be kept tracked rigorously and should be clearly identified in the final assessment report (Prox and Curran 2017). Figure 8.4 shows two different approaches employed for assessing the environmental impacts of using waste cooking oil (WCO) and poultry fat (PF) based biodiesel blends in urban buses in Iran (Rajaeifar et al. 2017b). Based on the figure, when considering ALCA of WCO and PF biodiesel blends, feedstock collection, transportation, biodiesel production and combustion stages are considered inside the system boundaries of the study. In such situation, all the relevant (background and foreground) data need to be collected as average data considering the current technologies while changes in demands and supply chains in the market as a result of biodiesel development are not considered.

By contrast, considering a CLCA of WCO and PF biodiesel blends (Fig. 8.4), the indirect effects of using these fuels are included in addition to the mentioned stages. More specifically, when using WCO and PF for biodiesel production, their demand in the market is bound to increase and consequently (in the most likely situation) their previous users should find alternative oils or so-called 'marginal oils'. Accordingly, removed WCO is compensated by palm oil while removed PF is substituted by a mixture of palm and soybean oils (Jørgensen et al. 2012; Rajaeifar

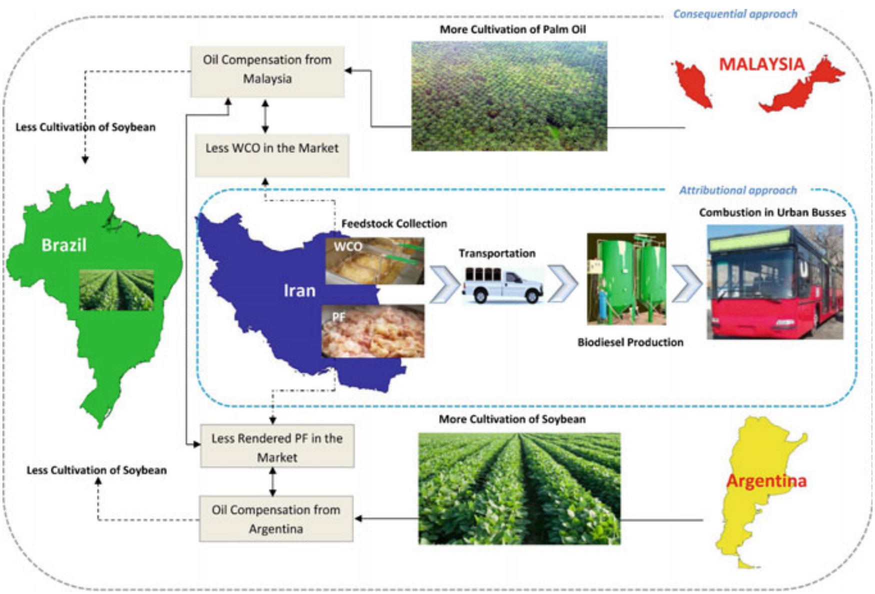

Fig. 8.4 Attributional and consequential approaches in assessing the environmental impacts of using waste cooking oil (WCO)- and poultry fat (PF)-based biodiesel blends in urban buses in Iran. With Permission from Rajaeifar et al. (2017b)

et al. 2017b). In this regard, Malaysia was identified as the marginal producer of palm oil in the global market while Argentina was identified as the marginal supplier of soybean oil to Iran. Therefore, the compensation of removed WCO oil and rendered PF (for biodiesel production) from the market implies more agricultural cultivation in these countries. Consequently, this leads to an increase in the production of some coproducts (i.e., palm kernel meal in Malaysia and soybean meal in Argentina). Increased production of such coproducts has also an indirect effect, i.e., decreased production of their marginal products. Since Brazil was identified as the marginal producer of soybean meal in the global market, the increased agricultural cultivation and consequent increase in the production of palm kernel meal and soybean meal leads to a decrease in the production of soybean meal (as well as its soybean oil) in Brazil. In this LCA approach, the indirect land use change impacts are also included and the marginal (background and foreground) data are collected considering the futuristic technologies.

Overall, while the main challenges in performing ALCA for biofuel systems (including biodiesels) focus on allocation procedures, the main challenges when using CLCA approach are generally attributed to quantifying the indirect effects of developing biofuels on the other cycles, i.e., food/feed/fiber (Wiloso and Heijungs 2013). This mainly includes quantifying/modeling the iLUC impacts as one of the major challenges faced by regulators when making specific choices among various biofuel alternatives s (Plevin et al. 2015). This issue has been neglected by many research studies on LCA of biofuels while taking into account such impacts could undermine the benefits attributed to the substitution of biofuels with their fossil counterparts (Searchinger et al. 2008; Zamagni et al. 2012; Ben Aoun and Gabrielle 2016). Likewise, unresolved debates in direct/indirect impacts from agricultural cultivation as well as allocation of coproducts have caused problems leading no clear distinction between ALCA and CLCA in most regionalized policy guidelines (Brander et al. 2008; van Dam et al. 2010). It seems that improving the global economic interaction models as well as developing the methods for more accurately calculating land use change emissions are the master keys for these challenges.

8.3.2 Inventory Analysis

LCI is the phase of collecting and quantifying inputs and outputs (as a flow model including all the emissions) inside the defined system boundary of a product throughout its life cycle. Accordingly, the quality of collected data as well as methods for quantifying emissions are the main concerns in the inventory analysis (Heijungs and Wiloso 2014). Therefore, data sources, quality, and their collection procedure as well as methodology applied to calculate emissions must be clearly and unambiguously presented in this stage from the starting point of a given life cycle to its end. Below, some typical LCI-related problems faced in biodiesel studies are discussed.

8.3.2.1 Agricultural Field Emissions

One of the most important steps in the LCI of biodiesel systems is the estimation of agricultural field emissions. The stage may be involved as the main stage like what is usually happened in first-generation feedstocks or may be indirectly involved in such agricultural activities happened as an indirect effect of some second-generation biodiesels. In the case of third-generation feedstock, agricultural cultivation stage mainly includes the cultivation of algae in pounds which is also an important but less complex issue.

The agricultural stage has been identified as the stage which introduces a lot of complexity and uncertainty in LCA of biofuel systems (Wiloso and Heijungs 2013). The complexity is the result of interactions between soil–water–air and chemical/organic nutrients. The uncertainty encompasses a wider concept related to indirect land use change impacts while also in the simplest form (without considering any indirect effect), the variability in soil structure and climate as well as in agricultural practice management scenarios could lead to substantial variations in LCA results.

In order to calculate field crop emissions, the nutrient balance must be identified by focusing on the most important nutrient inputs to and outputs from a farm. The main cycles which generally must be considered are carbon and nitrogen as well as the other elements such as phosphorous and potassium. Moreover, there are some undesirable inputs such as heavy metals which must be inventoried as well. The main activities responsible for the field crop emissions (or so-called 'on site emissions') are applying fertilizers/pesticides and land transformation. It is also worth quoting that soil and climate conditions affect the level of emissions as well. Overall, the following emissions are generally considered (Harris et al. 2015; Nemecek et al. 2016; Khoshnevisan et al. 2017):

1. Carbon dioxide emissions (to air) due to urea application (if any urea fertilizer is used).
2. Carbon dioxide emissions (to air) due to changes in carbon pools as a result of land transformation, occupation and restoration activities.
3. N_2O and CH_4 emissions (to air) as a result of land use change.
4. NH_3 and NO_x emissions (to air) as well as direct and indirect N_2O emissions (to air) due to the application of N-based fertilizers.
5. Nitrate leaching (to groundwater) due to the application of N-based fertilizers.
6. Nitrate run-off (to surface water) due to the application of N-based fertilizers.
7. Phosphorus leaching (to groundwater) due to the application of P-based fertilizers.
8. Phosphate run-off (to surface water) due to the application of P-based fertilizers.
9. Heavy metal emissions (to agricultural soil) and groundwater due to the application of N, P, and K-based fertilizers.
10. Tailpipe emissions (to air) from diesel/gasoline combustion during farm operations.

11. Emissions of pesticides (to agricultural soil).

There are three approaches for determining the field crop emissions, i.e., (1) measuring actual emission rates from the studied system, (2) applying emission values derived from literature in a case-by-case procedure, and (3) estimating potential emission rates through structured estimation methods (Brentrup et al. 2000). Using the first approach in order to determine field crop emissions is money- and time-consuming, and not applicable for many types of emissions. Moreover, field measurements generally show great variations and generally are representative of specific conditions at the time of measurement which is not necessarily appropriate for LCA purposes. A new update of emission values is often required when using emission values from the literature (the second approach) while the quality of the values is questioned (Brentrup et al. 2000).

The third approach, i.e., using structured estimation methods in order to estimate emission rates, is the most employed approach in LCA studies in which field crop emissions are considered. The term 'structured' refers to considering different impacts of soil condition, climate and agricultural practices alongside the dosage of a given nutrient as input. These types of methods can easily be employed with less effort, cost and uncertainty compared to direct measurements or values derived from the literature. Moreover, since the estimation methods simplify the complex conditions using structured frameworks, the quality of the estimated emission rates can be updated and improved in time. There are many types of models and guidelines for estimating the field crop emissions, some of them only model limited number of emissions, while others model most of emissions. Some examples are IPCC (2006), Nemecek et al. (2016), Birkved and Hauschild (2006), etc.

While methods for estimating field crop emissions are being further developed consistently, becoming more accurate on a daily basis, many challenges still remain in calculating agricultural field emissions mainly due to the (1) data gaps in long-term soil quality dynamics, (2) lack of LCIs on many active ingredients of pesticides, (3) lack of understanding of the pesticides' emissions mechanism when used in field operations, (4) inclusion of N_2O and CH_4 emissions from land use change activities, (5) modeling the emissions of NO_3 based on different pedo-climatic conditions and different management options as well as (6) adopting data related to the periods before and after agriculture in the assessments.

8.3.2.2 Land Use and Land Use Change

The issue of land use and land use change has become a very critical and important issue since it has been identified as a great contributor to global GHG emissions (Watson et al. 2000). The term land use is generally used for land transformation (period before agricultural activities), land occupation (period during agricultural activities), and land restoration (period after agricultural activities). Although there is no exact place for land use and land use change in the LCA framework, most of the studies and guidelines consider land transformation and land restoration activities as land use changes (Wiloso and Heijungs 2013), while land occupation is generally considered as land use activities. The main issue is not about the use of these terms instead of each other, but rather quantifying the impact of land use change using a sound and accurate framework is the current challenge in LCA studies. More specifically, despite the existing consensus on the inclusion of land use change impacts when assessing the environmental impacts of biofuel development, the resulting indicators suffer from a considerable deal of heterogeneity, significant inaccuracies, as well as high uncertainties (Cherubini and Strømman 2011; Fritz et al. 2013).

In the case of first-generation biodiesels (as well as the other first-generation biofuels), the increase of biodiesel usage will lead to an increase in the demand for the feedstock used for biodiesel production, with a subsequent feedstock shortage, and thus increased market prices of the feedstocks used. This situation would motivate those active in the agriculture industry, e.g., farmers for increasing their outputs through different mechanisms, i.e., (1) intensifying crop management systems to improve yields, (2) transforming uncultivated lands into agricultural land, and (3) substituting food/feed/fiber crops by energy crops (Ben Aoun and Gabrielle 2016). The second and third approaches could trigger land use change mechanisms either in direct or indirect ways. It is also worth quoting that the development of second-generation biodiesels could also result in such land use change impacts when the feedstock used for biodiesel production, e.g., PF and WCO, would also be used as raw materials in other industries. In such cases, the removed WCO or PF must be compensated by producing and importing oil crops elsewhere, presumably mainly fulfilled by the second and third mechanisms.

Direct Land Use Change (dLUC)

In biodiesel production/consumption systems, direct land use change (dLUC for short) takes place when new agricultural land is assigned to the production of feedstock for biodiesel production and the feedstock displaces a prior land use (e.g., conversion of degraded tropical rainforest or alang-alang grass lands to oil palm plantation). This substitution in land use may include the situation in which feedstock for biodiesel displaces other crops (used for food/feed/fiber purposes) in a cropping system. These situations as dLUC may cause changes in the carbon stock of the assigned land and result in global warming impact. The carbon stock generally exists in five different pools, i.e., above ground vegetation, below ground vegetation, dead wood, litter, and (most importantly) soil (Cherubini and Strømman 2011).

Depending on which type of land is transformed for the production of biodiesel feedstock, the net carbon emissions due to dLUC can be positive or negative. More specifically, when land with a high carbon stock (e.g., natural forest areas, pasture, and peatlands) is converted to agricultural land, a loss of carbon stocks may affect the whole carbon balance, strongly undermining the environmental performance of the given biodiesel compared with its fossil counterpart (Reijnders and Huijbregts 2008; Panichelli et al. 2009). Moreover, these types of transformation would lead to a decrease in biodiversity (Salaa et al. 2009). On the contrary, if biodiesel feedstocks are grown on set-aside or degraded lands or when perennial crops (e.g., oil palm) replace annual row crops, dLUC can contribute to increases in the carbon stock, and thus has a positive effect on the GHG balance of the biodiesel system (Styles and Jones 2007; Wu et al. 2008).

It is also worth quoting that the changes in carbon stocks are highly dependent on the previous and current agricultural practices, post-harvest activities, climate, and soil characteristics (Cherubini and Strømman 2011), and thus they require site-specific quantification. Nevertheless, methods have been developed to generalize and estimate changes in carbon pools by means of literature references, default values, or software tools capable of modeling soil carbon dynamics.

Indirect Land Use Change (iLUC)

Indirect land use change (iLUC for short) occurs when developments in biodiesel production cause changes in land use elsewhere. This situation generally happens when feedstock production for biodiesel takes place on lands currently used for food/feed/fiber crops and the demand for the former land use (i.e., food, feed, fiber) remains. Therefore, the removed agricultural production will relocate to other places in order to maintain the balance in the global market and prevent competitions among biodiesel and food/feed/fiber production domains (Gnansounou et al. 2008). Clearly, market mechanisms are the core of agricultural cultivation displacement. The existing challenges in quantifying iLUC impacts is mainly due to the complexity and speculative nature of the mechanisms involved in land use change. Such shortcomings could result in (1) lack of consensus on using one method for estimating iLUC impacts, (2) variability in iLUCs results, and (3) uncertainty of the LCA conclusions.

Although increased pressure on land worldwide, and thus the creation of iLUC impacts has been mainly associated with the development of first-generation feedstock (Ben Aoun and Gabrielle 2016), the development of second-generation feedstock may also bring about such effects when the feedstock is already used by other sectors rather than biofuels sector. For example, when the development of WCO and PF biodiesel is considered (Fig. 8.4), demands for WCO and rendered PF in the market are bound to increase and consequently (under the most possible circumstances) their previous users will inevitably try to find alternative sources of oil. Accordingly, the removed WCO could be compensated for instance, by palm oil while a mixture of palm and soybean oils could substitute removed PF. This situation necessitates more agricultural production elsewhere which causes iLUC impacts (Rajaeifar et al. 2017b). If the cultivation of feedstock for biodiesel production takes place on fallow, marginal, or degraded lands where no conventional crops are grown, no iLUC happens and the GHG balance can turn out to be more favorable (Cherubini and Strømman 2011).

There are three main approaches in dealing with iLUC effects including (1) use of historical data and statistical analysis, (2) using experts' opinion, and (3) applying economic equilibrium models. The first approach employs historical data from different sources and statistically analyzes them in order to identify possible relationships between the rate of feedstock production (for biofuels including biodiesel) in a given country and land use change (Ben Aoun and Gabrielle 2016). There are number of studies which employed this approach for estimating land use change impacts (Kim and Dale 2011; Overmars et al. 2011). In the second approach, the experts are supposed to have an understanding of the underlying market mechanisms in order to chase the possible iLUCs location and quality and predict their magnitude. This generally happens through estimating cause-effect relations in the market as well as through the simplification of market mechanisms (Bauen et al. 2010; Ben Aoun et al. 2013). Examples of employing such approaches are Dalgaard et al. (2008), Schmidt (2010), Reinhard and Zah (2011), Escobar et al. (2014) and Rajaeifar et al. (2017b).

Compared with the first and second approaches, the third approach could be more accurate and effective in estimating iLUC impacts since it is capable of modeling economic processes in the market. In fact, when using historical data or expert-based opinion approaches, market mechanisms are simplified and some other activities that can lead to land use change may not be considered. Therefore, the prediction of iLUC might not be accurate enough (Ben Aoun et al. 2013). The economic equilibrium models are based on the theory of perfect markets in economy. Accordingly, the response of supply and demand to price changes creates an equilibrium in which demand equals supply. This, in fact, forms the basis of the estimation for the iLUC impacts. The economic equilibrium models generally include two types of equilibrium models, i.e., partial and general equilibrium models which have been comprehensively explained by Ben Aoun and Gabrielle (2016).

Despite the existence of various methods for estimating iLUC impacts, there is a global interest in using economic models for estimating land use change impacts. This is ascribed to the fact that these models could generally determine the consequences of additional demands created by the development of biodiesel production/consumption systems on global land use. Nevertheless, economic models still need to be substantially improved in order to be more accurate and reliable. This could be achieved by making the estimation of markets response to price changes and producers/consumers preferences more realistic and less uncertain. Improving the quality of different databases concerning carbon stocks changes, fertilizer use, and gaseous emissions of nitrogen could also enhance the accuracy of the models used and reduce their uncertainty and variations, generally occurring when using different methods for estimating land use change impacts.

Apart from land use change attributed to biodiesel production, water footprint should also be taken into consideration. This is further highlighted given the anticipated water scarcity challenge and the resultant conflicts among countries in the near future. Therefore, a word of warning should also be added regarding the importance of the water availability and water footprint assessments in future LCA frameworks and guidelines. In another word, even if the challenges concerning the quantifying iLUC impacts will be resolved; the water availability as well as water footprint of biodiesel production/consumption systems will still be a limiting factor for future development of this alternative fuel. In this regard, water resources and availability estimations as well as water footprint assessment must also be included in decision-making for anticipating the possible impacts attributed to the indirect land use effect of biodiesel development.

8.3.2.3 Conversion Processes and Combustion Emissions

Biodiesel production/consumption systems include conversion processes through which the raw feedstock for biodiesel production is converted into biodiesel. Inventory data at this stage mainly include the upstream activities for the production of energy and materials used in the conversion process, emissions from the production of capital goods as well as emissions arisen from the conversion reaction itself. Data gaps and uncertainties in the conversion process are mainly attributed to developing technological routes, particularly, on an industrial scale. In this regard, the real impacts of the current production technology or the considered marginal technology could be under- or overestimated and therefore, a sensitivity analysis would be necessary.

As mentioned before, the combustion stage is the final stage in a 'well-to-wheel' life cycle of biodiesel in which tailpipe emissions from vehicles using biodiesel are measured. More specifically, the required inventory data on tailpipe emissions can be collected through laboratory chassis dynamometer tests or real-world tests. The most important issue when collecting inventory data for this stage is to ensure that the data would be representative of the real-world conditions. In line with that, the driving cycles chosen for laboratory chassis dynamometer must be selected or designed carefully according to the real-world conditions of the area/routes/fleet at which biodiesel is intended to be used. In case of real-world tests, it is recommended to perform a set of real-driving tests considering statistical criteria (e.g., using statistical designs), ambient factors (e.g., temperature, humidity, and passenger counts), and vehicle factors (engine model year, engine type, mileage traveled before and during the experiments, engine oil type and viscosity). Moreover, it is suggested to select various routes and various traffic situations in different weekdays for performing real-world driving tests. These would increase the validity of and options for extrapolating the results, especially when assessing tailpipe emissions in a transportation fleet is considered.

8.3.2.4 Biogenic Carbon

Like other biofuel systems, biodiesel production/consumption systems can absorb and sequester CO_2 from the atmosphere. More specifically, agricultural crops are capable of fixing atmospheric CO_2 during their growth period, while the absorbed C is released when the crops/resultant products are subjected to the combustion process. Nevertheless, this is not a sufficient reason for assuming biodiesel production/consumption systems as carbon neutral ones, i.e., assuming all emissions arisen from biodiesel combustion as biogenic. In fact, such systems require a significant amount of fossil inputs whose consumption (or production) increase the atmospheric CO_2 level. These fossil inputs are generally consumed during planting, fertilization, harvesting, oil extraction, transportation, as well as biodiesel production and combustion. For example, large amounts of N-based fertilizers are consumed annually for agricultural fertilization and the production of these fertilizers impose a significant deal of environmental burden, i.e., GHG emissions released to the atmosphere.

As for biodiesel combustion, it is generally assumed by many studies that all the CO_2 emissions arisen from biodiesel combustion have a biogenic nature. However, from the chemical point of view, biodiesel is made through a reaction between an alcohol and triglycerides, and thus the C atoms of the alcohol used also contribute to the resultant methyl esters. Therefore, if the alcohol such as methanol (the common alcohol in biodiesel production) used in the biodiesel production stage is of fossil origin, not all the CO_2 emissions from the combustion of biodiesel could be regarded as biogenic. Therefore, it is important to distinguish the emissions associated with the biogenic and non-biogenic carbon moieties; this is not a facile job though. In better words, it is suggested to calculate their partitioning among all major carbon-based tailpipe emissions such as CO_2, CO, PM and non-methane hydrocarbons (NMHC) (Sheehan et al. 1998). It is important to take into account all carbon-based tailpipe emissions due to the fact that under real-world conditions, engines do not completely combust all the carbon in the fuel, and thus the whole carbon contained in a given fuel is not combusted as CO_2. It is also worth mentioning that the carbon emission components other than CO_2, could not be considered as biogenic since they will not be absorbed throughout the cycle, i.e., over the plant's growth period.

Another challenging issue in biogenic carbon cycles occurs when the agricultural production stage results in coproducts (e.g., palm oil and palm kernel oil). Under such circumstances, a part of the absorbed CO_2 is allocated to each of the coproducts (Wiloso and Heijungs 2013). Using an appropriate allocation method is the center of current debate among academics and more research is needed in order to reach a global consensus. The final challenge regarding the biogenic nature of biodiesel is attributed to a time difference between CO_2 fixation and release. Development of dynamic LCA methods could help to account for such situations.

Although there is no consensus regarding how to treat biogenic carbon, the most important issue is to avoid double counting of CO_2 emissions. To achieve that, (1) the inclusion or exclusion of carbon sequestration, (2) the inclusion or exclusion of biogenic carbon, and (3) calculating the share of biomass-oriented carbon in final CO_2 released by biodiesel combustion must be explicitly stated in the inventory analysis of a study.

8.3.2.5 Multifunctional Unit Processes

The issue of multifunctional unit processes occurs when a unit process yields more than one functional flow. Multifunctional unit processes can take place under three main conditions, i.e., coproduction, combined waste processing, and recycling

(Wiloso and Heijungs 2013). Under such conditions, it is generally preferred to determine the environmental burdens of a given product among the others. An example in biodiesel production/consumption systems is biodiesel production from palm oil in which it is important to determine the environmental burdens attributed to palm oil and distinguishing it from the environmental burdens related to palm kernel oil. The ISO standard (ISO14044 2006) describes multifunctionality options rather not in the goal and scope definition, but in the later stage of the Inventory analysis. This avoids predefining or dictating a preferred option and instead could help with considering the relevancy and adequacy of the options quantitatively in the inventory phase (Baitz 2017).

In order to deal with multifunctional unit processes, there are three approaches available as suggested by existing guidelines but in different order of priority, i.e., subdivision, system expansion (including substitution), and allocation (or partitioning). Based on the ISO standard, it is preferred to avoid burden allocation mainly using the first two methods. Nevertheless, using subdivision requires precise separation between the main processes considering the related mass and energy balances. Furthermore, using system expansion or product displacement could be more difficult and uncertain, as it requires comprehensive investigation of the whole market of all the output products, including so-called "avoided" processes.

A major challenge in the third option, i.e., allocation, is determining the criteria needed for attributing emissions, waste, and upstream inputs to various coproducts. The criteria often used include ratios of mass, energy, and economic value. There are also studies which tried to avoid allocation through choosing an appropriate FU, e.g., input-oriented FUs (Cherubini and Strømman 2011) as well as the two options elaborated earlier. A detailed discussion of the possible allocation methods, with their advantages and disadvantages, can be found in the literature (Ekvall and Finnveden 2001; Curran 2007; Heijungs and Guinée 2007).

8.3.3 Impact Assessment

LCIA is the third phase in conducting a life cycle study. In LCIA, the inventory data are reflected in the impact categories (Wolf et al. 2010). This phase consists of a number of activities including the selection of impact category, classification, characterization, normalization, grouping, weighting, and data quality analysis. Among these activities, the first three are mandatory, while the rest are optional (ISO14044 2006). The most important fact about impact assessment is to properly choose a set of relevant impact categories to measure the potential environmental burdens of a given biodiesel production/consumption system in all environmental dimensions, i.e., human health, ecosystem quality, and resources. In this regard, the set of chosen impact categories must be comprehensive as much as possible.

LCA studies on biodiesel production/consumption systems generally fall into three types of impact assessment, i.e., energy input–output analysis, global warming, and other life cycle impact categories (Cherubini and Strømman 2011).

Energy input–output analysis or energy analysis is aimed at quantifying the efficiency of a given renewable energy production (i.e., biodiesel) and determines the possible nonrenewable energy savings through biodiesel production. The most important index in these types of studies is fossil energy ratio (FER) which shows the actual benefit obtained from a biodiesel production/consumption system by taking into account the amount of fossil resources consumed in the life cycle of biodiesel production/consumption. Nevertheless, it should be mentioned that the energy input–output analysis mostly shows the technical feasibility of the biodiesel production/consumption systems rather than being an impact assessment method in principle (Wiloso and Heijungs 2013). However, its respective results could be later analyzed and interpreted from the environmental point of view. The transportation distances and methods as well as the type of allocation method used to allocate energy flow between coproducts (if required) are the most important issues which could significantly affect the results of energy analysis studies and, therefore, these must be performed accurately, including a sensitivity analysis.

Global warming is one of the most common indices used in LCA of biodiesels by which a list of GHG emissions arisen from all the processes involved in the life cycle are collected and then translated into CO_2 equivalents. Although global warming is included in most of LCA studies performed on biodiesel production/consumption, the issue of biogenic carbon as well as land use change still remains as the main challenge, mostly neglected in many research studies as elaborated previously. These issues could significantly affect the global warming contribution of a given biodiesel production/consumption system and turn the results from favorable to unfavorable, or the other way around. Other life cycle impact categories include a variety of impact categories, e.g., eutrophication, acidification, aquatic ecotoxicity, terrestrial ecotoxicity, carcinogens, noncarcinogens, respiratory organics/inorganics, etc., which have been used in a number of LCA studies of biodiesel (Panichelli et al. 2009; Xue et al. 2012; Rajaeifar et al. 2016; Rajaeifar et al. 2017a; Sousa et al. 2017).

Overall, a common weakness of most studies conducted on biodiesel LCA is attributed to the lack of sufficient coverage of impact categories. In fact, failure to address key impact categories may bring about incomplete or unreliable information, creating biased decisions. Therefore, it has been suggested to choose a set of impact categories in agreement with the goal and scope of the study, while considering a default minimum in order to reduce the risk of biased decisions (Wiloso and Heijungs 2013). Moreover, due to the fact that water scarcity challenge is expected to introduce more serious troubles in the near future, water footprint must also be included as an important impact category in future LCA studies on biodiesel production. The most important issue regarding the current impact categories in LCA studies is the fact that all the current impact categories consider the potential impact or maximum possible impact only. In this regard, future attempts could also be devoted to including the exposure effects of different emissions in LCA studies since a system with higher level of pollution but in low population (humans or biodiversity) areas may perform environmentally better compared with a system with lower level of environmental emissions but at more populated areas.

8.3.3.1 Regionalized Impact Assessment

Regionalization in LCA studies is generally performed for inventories and impact assessment methods. Collection of activity data as well as region-specific background data is required in order to accurately show all the relevant processes involved and to enable the application of geographically explicit impact assessment models (Morais et al. 2016). In view of the impact assessment methods used, there are some environmental impacts which could have different effects on the human health/ecosystem quality depending on the characteristics of the receiving environment (i.e., the location of the activity). The variations in the resulting impacts of such impact categories generally relate to the characteristics of both the emitting source and the receiving environment (Finnveden et al. 2009).

When the system boundary of a study includes an agricultural stage, the use of regionalized impact assessment methods could be of importance since the impacts analyzed are clearly site-dependent. Therefore, impact assessment methods must meet some criteria which clearly reflect the regional conditions of the agricultural system included in a biodiesel production/consumption system under investigation. Regionalization is not of concern for global impact categories such as global warming or stratospheric ozone depletion since these impacts are independent of where the emissions occur. Instead, there are some impact categories which are often regional or even local in nature and thus, they need to be set on regional scale. Although regionalization in LCA studies is rarely performed in practice (Mutel and Hellweg 2009), recent developments in regionalization have focused on enhancing characterization methods for regional impact categories in order to be able to apply them in a more consistent way in different regions all over the world (Hauschild and Huijbregts 2015) and to further improve the accuracy of LCIA methods. Among the attempts aimed at the regionalization of impacts is the implementation of impact assessment relating to water use (Boulay et al. 2011; Verones et al. 2013) and land use (Elshout et al. 2014), as well as acidification and terrestrial eutrophication (Seppälä et al. 2006). Besides, attempts have also been made in developing site-dependent characterization for LCIA which are appropriate for processes in Europe, the USA, and some other certain countries (Finnveden et al. 2009).

The main aim in regionalizing an impact category must be devoted to addressing how the impacts will manifest themselves on local or regional scales. To achieve this goal, accurate assessments must be performed in order to provide a process under investigation with spatial variability so that it can be applied on all geographical scales. Moreover, in order to obtain more representative impact estimates in relation to location-dependent impacts, the inherent differences associated with variability in soil types and complex interactions with local climates must be considered as well (Wiloso and Heijungs 2013).

8.4 Conclusions

Biodiesel has attracted a great deal of attention throughout the world as a promising substitute for petroleum diesel. From an LCA point of view, biodiesel production/consumption systems face similar challenges as other biofuel systems. This is due to the fact that such systems directly or indirectly involve an agricultural stage which brings about several complex and challenging issues in estimating the real environmental impacts. In addition to that, there is a necessity of reaching a consensus on methods used for selecting a functional unit, setting system boundaries, selecting impact categories, allocating multifunctional processes as well as quantifying land use changes and biogenic carbon. Most importantly, future policy decisions should be focused on the best use of fertile lands for climate change mitigation as well as the best use of water for producing goods in the agriculture sector. Therefore, the quantification of the land use change impacts as well as water footprint originated from the development of feedstock for biodiesel are very important issues for the development of more efficient environmentally friendly biodiesel production/consumption systems in the future. As a consequence, establishing a sound and scientific framework in order to efficiently characterize land use change impacts and water use assessments in future LCA frameworks is of prime importance for future LCA studies.

References

Aghbashlo M, Tabatabaei M, Mohammadi P, Khoshnevisan B, Rajaeifar MA, Pakzad M (2017) Neat diesel beats waste-oriented biodiesel from the exergoeconomic and exergoenvironmental point of views. Energy Convers Manag 148:1–15

Altamirano CAA, Yokoyama L, de Medeiros JL, Araújo OdQF (2016) Ethylic or methylic route to soybean biodiesel? Tracking environmental answers through life cycle assessment. Appl Energy 184:1246–1263

Ashokkumar V, Salim MR, Salam Z, Sivakumar P, Chong CT, Elumalai S, Suresh V, Ani FN (2017) Production of liquid biofuels (biodiesel and bioethanol) from brown marine macroalgae Padina tetrastromatica. Energy Convers Manag 135:351–361

Baitz M (2017) Attributional life cycle assessment. In: Curran M (ed) Goal and scope definition in life cycle assessment. Springer, Dordrecht. The complete world of life cycle assessment. Springer, Dordrecht

Baskar G, Aiswarya R (2016) Trends in catalytic production of biodiesel from various feedstocks. Renew Sustain Energy Rev 57:496–504

Bauen A, Chudziak C, Vad K, Watson P (2010) A causal descriptive approach to modelling the GHG emissions associated with the indirect land use impacts of biofuels. E4Tech, London

Baumann H, Tillman A-M (2004) The Hitch Hiker's guide to LCA. An orientation in life cycle assessment methodology and application. External Organization

Ben Aoun W, Gabrielle B (2016) Life cycle assessment and land-use changes: effectiveness and limitations. In: Gnansounou E, Pandey A (eds) Life-cycle assessment of biorefineries. Elsevier

Ben Aoun W, Gabrielle B, Gagnepain B (2013) The importance of land use change in the environmental balance of biofuels. In: Oilseeds and fats, crops and lipids, vol 1

Birkved M, Hauschild MZ (2006) PestLCI—a model for estimating field emissions of pesticides in agricultural LCA. Ecol Model 198:433–451

Boulay A-M, Bulle C, Bayart J-B, Deschênes L, Margni M (2011) Regional characterization of freshwater use in LCA: modeling direct impacts on human health. Environ Sci Technol 45:8948–8957

Brander M, Tipper R, Hutchison C, Davis G (2008) Technical paper: consequential and attributional approaches to LCA: a guide to policy makers with specific reference to greenhouse gas LCA of biofuels. Econometrica Press

Brentrup F, Küsters J, Lammel J, Kuhlmann H (2000) Methods to estimate on-field nitrogen emissions from crop production as an input to LCA studies in the agricultural sector. Int J Life Cycle Assess 5:349–357

Cherubini F, Strømman AH (2011) Life cycle assessment of bioenergy systems: state of the art and future challenges. Biores Technol 102:437–451

Choo YM, Muhamad H, Hashim Z, Subramaniam V, Puah CW, Tan Y (2011) Determination of GHG contributions by subsystems in the oil palm supply chain using the LCA approach. Int J Life Cycle Assess 16:669–681

Curran MA (2007) Co-product and input allocation approaches for creating life cycle inventory data: a literature review. Int J Life Cycle Assess 12:65–78

Curran MA (2017) Overview of goal and scope definition in life cycle assessment. Goal and scope definition in life cycle assessment. In: LCA compendium—The complete world of life cycle assessment. Springer, pp 1–62

Dalgaard R, Schmidt J, Halberg N, Christensen P, Thrane M, Pengue WA (2008) LCA of soybean meal. Int J Life Cycle Assess 13:240

Demirbas A (2009) Biodiesel from waste cooking oil via base-catalytic and supercritical methanol transesterification. Energy Convers Manag 50:923–927

Demirbas MF (2011) Biofuels from algae for sustainable development. Appl Energy 88:3473–3480

Dufour J, Iribarren D (2012) Life cycle assessment of biodiesel production from free fatty acid-rich wastes. Renew Energy 38:155–162

Ekvall T, Finnveden G (2001) Allocation in ISO 14041—a critical review. J Clean Prod 9:197–208

Ekvall T, Weidema BP (2004) System boundaries and input data in consequential life cycle inventory analysis. Int J Life Cycle Assess 9:161–171

Elkington J (1997) Cannibals with forks. In: The triple bottom line of 21st century, vol 73

Elshout PM, van Zelm R, Karuppiah R, Laurenzi IJ, Huijbregts MA (2014) A spatially explicit data-driven approach to assess the effect of agricultural land occupation on species groups. Int J Life Cycle Assess 19:758–769

Escobar N, Ribal J, Clemente G, Sanjuán N (2014) Consequential LCA of two alternative systems for biodiesel consumption in Spain, considering uncertainty. J Clean Prod 79:61–73

Finnveden G, Hauschild MZ, Ekvall T, Guinée J, Heijungs R, Hellweg S, Koehler A, Pennington D, Suh S (2009) Recent developments in life cycle assessment. J Environ Manage 91:1–21

Fritz S, See L, Valin H (2013) Current issues and uncertainties in estimating global land availability for biofuel production. Taylor & Francis

Georgogianni K, Kontominas M, Pomonis P, Avlonitis D, Gergis V (2008) Conventional and in situ transesterification of sunflower seed oil for the production of biodiesel. Fuel Process Technol 89:503–509

Ghobadian B, Rahimi H, Nikbakht A, Najafi G, Yusaf T (2009) Diesel engine performance and exhaust emission analysis using waste cooking biodiesel fuel with an artificial neural network. Renew Energy 34:976–982

Gnansounou E, Panichelli L, Dauriat A, Villegas JD (2008) Accounting for indirect land-use changes in GHG balances of biofuels: review of current approaches

Guinée J, Heijungs R (2017) Introduction to life cycle assessment. In: Sustainable supply chains. Springer, pp 15–41

Guinée JB (2002) Handbook on life cycle assessment operational guide to the ISO standards. Int J Life Cycle Assess 7:311
Harris Z, Spake R, Taylor G (2015) Land use change to bioenergy: a meta-analysis of soil carbon and GHG emissions. Biomass Bioenergy 82:27–39
Hauschild MZ, Huijbregts MAJ (2015) Introducing life cycle impact assessment. In: Life cycle impact assessment. Springer, pp 1–16
Hawkins TR, Singh B, Majeau-Bettez G, Strømman AH (2013) Comparative environmental life cycle assessment of conventional and electric vehicles. J Ind Ecol 17:53–64
Heijungs R, Guinée JB (2007) Allocation and 'what-if'scenarios in life cycle assessment of waste management systems. Waste Manag 27:997–1005
Heijungs R, Wiloso EI (2014) Life cycle assessment of bioenergy systems. In: Wang L (ed) Sustainable bioenergy production, pp 99–114
Hodaifa G, Ochando-Pulido J, Rodriguez-Vives S, Martinez-Ferez A (2013) Optimization of continuous reactor at pilot scale for olive-oil mill wastewater treatment by Fenton-like process. Chem Eng J 220:117–124
Hosenuzzaman M, Rahim N, Selvaraj J, Hasanuzzaman M, Malek A, Nahar A (2015) Global prospects, progress, policies, and environmental impact of solar photovoltaic power generation. Renew Sustain Energy Rev 41:284–297
Ibenholt K (2002) Materials flow analysis and economic modelling. In: Handbook of industrial ecology. Edward Elgar, Cheltenham, pp 177–184
IPCC (2006) Guidelines for national greenhouse gas inventories, Agriculture, forestry and other land use, vol. 4. Intergovernmental Panel on Climate Change
ISO14044 (2006) Environmental management. Life cycle assessment requirements and guidelines. ISO 14044 International Standard International Organization for Standardization
ISO14045 (2012) Environmental management—eco-efficiency assessment of product systems—principles, requirements and guidelines. ISO 14045 International Standard International Organization for Standardization
ISO14046 (2014). Environmental management—water footprint—principles, requirements and guidelines. ISO 14046 International Standard International Organization for Standardization
Jiaqiang E, Liu T, Yang W, Li J, Gong J, Deng Y (2016) Effects of fatty acid methyl esters proportion on combustion and emission characteristics of a biodiesel fueled diesel engine. Energy Convers Manag 117:410–419
Jørgensen A, Bikker P, Herrmann IT (2012) Assessing the greenhouse gas emissions from poultry fat biodiesel. J Clean Prod 24:85–91
Khoshnevisan B, Rafiee S, Tabatabaei M, Ghanavati H, Mohtasebi SS, Rahimi V, Shafiei M, Angelidaki I, Karimi K (2017) Life cycle assessment of castor-based biorefinery: a well to wheel LCA. Int J Life Cycle Assess 1–18
Kim S, Dale BE (2011) Indirect land use change for biofuels: testing predictions and improving analytical methodologies. Biomass Bioenergy 35:3235–3240
Kumara AS, Maheswarb D, Reddyc KVK (2009) Comparison of diesel engine performance and emissions from neat and transesterified cotton seed oil. Jordan J Mech Ind Eng 3
Lee RA, Lavoie J-M (2013) From first-to third-generation biofuels: challenges of producing a commodity from a biomass of increasing complexity. Anim Front 3:6–11
Lee W-J, Liu Y-C, Mwangi FK, Chen W-H, Lin S-L, Fukushima Y, Liao C-N, Wang L-C (2011) Assessment of energy performance and air pollutant emissions in a diesel engine generator fueled with water-containing ethanol–biodiesel–diesel blend of fuels. Energy 36:5591–5599
Liew WL, Kassim MA, Muda K, Loh SK, Affam AC (2015) Conventional methods and emerging wastewater polishing technologies for palm oil mill effluent treatment: a review. J Environ Manag 149:222–235
Lim S, Lee KT (2011) Parallel production of biodiesel and bioethanol in palm-oil-based biorefineries: life cycle assessment on the energy and greenhouse gases emissions. Biofuels Bioprod Biorefin 5:132–150

Lim SL, Wu TY, Clarke C (2014) Treatment and biotransformation of highly polluted agro-industrial wastewater from a palm oil mill into vermicompost using earthworms. J Agric Food Chem 62:691–698

Lin J, Babbitt CW, Trabold TA (2013) Life cycle assessment integrated with thermodynamic analysis of bio-fuel options for solid oxide fuel cells. Biores Technol 128:495–504

Ma F, Hanna MA (1999) Biodiesel production: a review. Biores Technol 70:1–15

Malça J, Freire F (2011) Life-cycle studies of biodiesel in Europe: a review addressing the variability of results and modeling issues. Renew Sustain Energy Rev 15:338–351

Martin B (2017) Attributional life cycle assessment. In: Curran MA (ed) Goal and scope definition in life cycle assessment. LCA compendium—The complete world of life cycle assessment. Springer, pp 123–143

Mohammadi P, Nikbakht AM, Tabatabaei M, Farhadi K, Mohebbi A (2012) Experimental investigation of performance and emission characteristics of DI diesel engine fueled with polymer waste dissolved in biodiesel-blended diesel fuel. Energy 46:596–605

Morais TG, Teixeira RF, Domingos T (2016) Regionalization of agri-food life cycle assessment: a review of studies in Portugal and recommendations for the future. Int J Life Cycle Assess 21:875–884

Moreno AO, Dorantes L, Galíndez J, Guzmán RI (2003) Effect of different extraction methods on fatty acids, volatile compounds, and physical and chemical properties of avocado (Persea americana Mill.) oil. J Agric Food Chem 51:2216–2221

Motasemi F, Ani FN (2012) A review on microwave-assisted production of biodiesel. Renew Sustain Energy Rev 16:4719–4733

Mutel CL, Hellweg S (2009) Regionalized life cycle assessment: computational methodology and application to inventory databases. Environ Sci Technol 43:5797–5803

Nemecek T, Schnetzer J, Reinhard J (2016) Updated and harmonised greenhouse gas emissions for crop inventories. Int J Life Cycle Assess 21:1361–1378

Nicoletti G, Arcuri N, Nicoletti G, Bruno R (2015) A technical and environmental comparison between hydrogen and some fossil fuels. Energy Convers Manag 89:205–213

Overmars KP, Stehfest E, Ros JP, Prins AG (2011) Indirect land use change emissions related to EU biofuel consumption: an analysis based on historical data. Environ Sci Policy 14:248–257

Panichelli L, Dauriat A, Gnansounou E (2009) Life cycle assessment of soybean-based biodiesel in Argentina for export. Int J Life Cycle Assess 14:144–159

Plevin RJ, Beckman J, Golub AA, Witcover J, O'Hare M (2015) Carbon accounting and economic model uncertainty of emissions from biofuels-induced land use change. Environ Sci Technol 49:2656–2664

Prox M, Curran MA (2017) Consequential life cycle assessment. In: Curran MA (ed) Goal and scope definition in life cycle assessment. LCA compendium—The complete world of life cycle assessment. Springer, pp 145–160

Rajaeifar MA, Abdi R, Tabatabaei M (2017a) Expanded polystyrene waste application for improving biodiesel environmental performance parameters from life cycle assessment point of view. Renew Sustain Energy Rev 74:278–298

Rajaeifar MA, Akram A, Ghobadian B, Rafiee S, Heidari MD (2014) Energy-economic life cycle assessment (LCA) and greenhouse gas emissions analysis of olive oil production in Iran. Energy 66:139–149

Rajaeifar MA, Akram A, Ghobadian B, Rafiee S, Heijungs R, Tabatabaei M (2016) Environmental impact assessment of olive pomace oil biodiesel production and consumption: a comparative lifecycle assessment. Energy 106:87–102

Rajaeifar MA, Ghobadian B, Davoud Heidari M, Fayyazi E (2013) Energy consumption and greenhouse gas emissions of biodiesel production from rapeseed in Iran. J Renew Sustain Energy 5:063134

Rajaeifar MA, Tabatabaei M, Abdi R, Latifi AM, Saberi F, Askari M, Zenouzi A, Ghorbani M (2017b) Attributional and consequential environmental assessment of using waste cooking oil-and poultry fat-based biodiesel blends in urban buses: a real-world operation condition study. Biofuel Res J 4:638–653

Reijnders L, Huijbregts M (2008) Biogenic greenhouse gas emissions linked to the life cycles of biodiesel derived from European rapeseed and Brazilian soybeans. J Clean Prod 16:1943–1948
Reinhard J, Zah R (2011) Consequential life cycle assessment of the environmental impacts of an increased rapemethylester (RME) production in Switzerland. Biomass Bioenergy 35:2361–2373
Sáez-Bastante J, Ortega-Román C, Pinzi S, Lara-Raya F, Leiva-Candia D, Dorado M (2015) Ultrasound-assisted biodiesel production from Camelina sativa oil. Biores Technol 185:116–124
Salaa O, Saxa D, Lesliea H (2009) Biodiversity consequences of increased biofuel production. In: Howarth RW, Bringezu S (eds) Environmental consequences and interactions with changing land use. Proceedings of the scientific committee on problems of the environment (scope) international biofuels project rapid assessment, Gummersbach Germany, Cornell University, Ithaca NY, USA
Sander K, Murthy GS (2010) Life cycle analysis of algae biodiesel. Int J Life Cycle Assess 15:704–714
Schmidt J (2007) Life cycle assessment of rapeseed oil and palm oil. Thesis, Part 3: Life cycle inventory of rapeseed oil and palm oil. Department of Development and Planning, Aalborg University, Aalborg
Schmidt JH (2010) Comparative life cycle assessment of rapeseed oil and palm oil. Int J Life Cycle Assess 15:183–197
Searchinger T, Heimlich R, Houghton RA, Dong F, Elobeid A, Fabiosa J, Tokgoz S, Hayes D, Yu T-H (2008) Use of US croplands for biofuels increases greenhouse gases through emissions from land-use change. Science 319:1238–1240
Seppälä J, Posch M, Johansson M, Hettelingh J-P (2006) Country-dependent characterisation factors for acidification and terrestrial eutrophication based on accumulated exceedance as an impact category indicator (14 pp). Int J Life Cycle Assess 11:403–416
Shah S, Sharma A, Gupta M (2005) Extraction of oil from Jatropha curcas L. seed kernels by combination of ultrasonication and aqueous enzymatic oil extraction. Biores Technol 96:121–123
Sheehan J, Camobreco V, Duffield J, Graboski M, Shapouri H (1998) Life cycle inventory of biodiesel and petroleum diesel for use in an urban bus. Final report. National Renewable Energy Lab, Golden, CO (US)
Singh A, Olsen SI, Nigam PS (2011) A viable technology to generate third-generation biofuel. J Chem Technol Biotechnol 86:1349–1353
Singh A, Olsen SI, Pant D (2013) Importance of life cycle assessment of renewable energy sources. In: Life cycle assessment of renewable energy sources. Springer, pp1–11
Sousa VM, Luz SM, Caldeira-Pires A, Machado FS, Silveira CM (2017) Life cycle assessment of biodiesel production from beef tallow in Brazil. Int J Life Cycle Assess 22:1837–1850
Stojković IJ, Stamenković OS, Povrenović DS, Veljković VB (2014) Purification technologies for crude biodiesel obtained by alkali-catalyzed transesterification. Renew Sustain Energy Rev 32:1–15
Styles D, Jones MB (2007) Energy crops in Ireland: quantifying the potential life-cycle greenhouse gas reductions of energy-crop electricity. Biomass Bioenergy 31:759–772
Thomassen MA, Dalgaard R, Heijungs R, De Boer I (2008) Attributional and consequential LCA of milk production. Int J Life Cycle Assess 13:339–349
Tran D-T, Chang J-S, Lee D-J (2017) Recent insights into continuous-flow biodiesel production via catalytic and non-catalytic transesterification processes. Appl Energy 185:376–409
UNCED (1992) Report of the united nation conference on environment and development
van Dam J, Junginger M, Faaij AP (2010) From the global efforts on certification of bioenergy towards an integrated approach based on sustainable land use planning. Renew Sustain Energy Rev 14:2445–2472
Van Zutphen J, Wijbrans R (2012) LCA GHG emissions in production and combustion of Malaysian palm oil biodiesel. J Oil Palm Environ Health (JOPEH) 2

Verones F, Saner D, Pfister S, Baisero D, Rondinini C, Hellweg S (2013) Effects of consumptive water use on biodiversity in wetlands of international importance. Environ Sci Technol 47:12248–12257

Watson R, Noble I, Bolin B, Ravindranath NH, Verardo D, Andrasko K, Apps M, Brown S, Farquhar G, Goldberg D (2000) Summary for policymakers: land use, land-use change, and forestry

Weidema B, Wenzel H, Petersen C, Hansen K (2004) The product, functional unit and reference flows in LCA. Environ News 70:1–46

Wiloso EI, Heijungs R (2013) Key issues in conducting life cycle assessment of bio-based renewable energy sources. In: Life cycle assessment of renewable energy sources. Springer, pp 13–36

Wolf M-A, Chomkhamsri K, Brandao M, Pant R, Ardente F, Pennington DW, Manfredi S, de Camillis C, Goralczyk M (2010). ILCD handbook-general guide for life cycle assessment-detailed guidance

Wu M, Wu Y, Wang M (2008) Mobility chains analysis of technologies for passenger cars and light duty vehicles fueled with biofuels: application of the Greet model to project the role of biomass in America's energy future (RBAEF) project. Argonne National Laboratory (ANL)

Xue X, Collinge WO, Shrake SO, Bilec MM, Landis AE (2012) Regional life cycle assessment of soybean derived biodiesel for transportation fleets. Energy Policy 48:295–303

Yu N, Xing D, Li W, Yang Y, Li Z, Li Y, Ren N (2017) Electricity and methane production from soybean edible oil refinery wastewater using microbial electrochemical systems. Int J Hydrogen Energy 42:96–102

Zamagni A, Guinée J, Heijungs R, Masoni P, Raggi A (2012) Lights and shadows in consequential LCA. Int J Life Cycle Assess 17:904–918